EFFECT OF REDUCTANT INJECTION ON CHROMITE SMELTING

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ABSTRACT

A small-scale solids-injection system that can be used to inject a variety of materials into a bath of molten metal or slag, using a graphite top-lance, has been developed in-house at Mintek. Mintek's plasma-furnace technology has a wide range of applications, all of which could potentially utilize this injection equipment. An immediate application, however, was perceived in chromite smelting. The smelting rates of chromite in open-bath plasma furnaces per unit furnace volume could be significantly increased, lowering both the capital costs and electrical energy costs.

Pilot-scale smelting tests were therefore carried out at Mintek to determine whether the throughput of chromite to a d.c. plasma-arc furnace could be increased by stirring of the bath and submerged injection of the reductant. During a six-day continuous campaign, feed batch masses of 111 kg were processed at power levels of 140 to 180 kW and at feed rates of up to 100 kg/h in an open-bath plasma furnace with an internal diameter of 0.5 m. The chromite reduction rate was monitored by taking dip samples of the slag bath at regular intervals.

The consumption of the graphite top-lance was low (<0.2 kg per hour of submerged operation), and a graphite lance has therefore been proved to be effective in smelting processes. A sufficiently large, and particularly deep, slag bath must be available, and the flowrate of the stirring/carrier gas must be balanced with the volume of the bath if stirring and injection are to have a beneficial influence on chromite smelting. Extensive experimental work still needs to be done to optimize nitrogen stirring of the molten slag bath, and particularly submerged injection of the reductant during chromite smelting in an open-bath plasma-arc furnace.

LIST OF SYMBOLS

J amount of material passing per unit time through unit area of a plane at right angles to the direction of material flow

A surface area

δ boundary layer thickness

$\dfrac{dc}{dx}$ concentration gradient.

D mass diffusivity

1 INTRODUCTION

During the past decade, injection metallurgy has become an important tool for metallurgical operations. To facilitate research into this field, a small-scale solids-injection system, that has the ability to inject a variety of materials, has been developed in-house at Mintek.

Mintek's plasma-furnace technology has a wide range of applications, all of which could potentially utilize this injection equipment. An immediate application, however, was perceived in chromite smelting. Mintek has been actively involved with chromite smelting in open-bath d.c. plasma-arc furnaces since 1979. The smelting rates of chromite per unit furnace volume could be significantly increased, lowering both the capital costs and electrical energy costs.

1.1 Perceived Benefits of Injection Metallurgy for Chromite Smelting

The possible rate-limiting steps in chromite reduction are:

(i)   chromite dissolution[1]
(ii)   transport of dissolved Cr_2O_3/CrO to a slag-carbon or slag-metal interface[1]
(iii)   heat transfer from the arc attachment region to the molten slag-metal bath.

Injection of the reductant into the slag bath should significantly improve the kinetics of the process, regardless of which of the above mechanisms apply.

1.1.1 Mass Transfer

At the high temperature prevailing in pyrometallurgical operations, the overall rate is usually controlled by mass transport of material. The rate for mass transport can be written as:

$$J = A \; \frac{D}{\delta} \; \frac{dc}{dx} . \tag{1}$$

From equation (1), it can be deduced that the reaction rate can be increased by increasing the surface area A and by decreasing the boundary-layer thickness δ. The surface area can be increased by breaking up solids into fine powders, liquids into droplets, and gases into small bubbles; boundary-layer thickness can be minimized by stirring of the liquid bath. Both of these objectives can be achieved by injecting a combination of solid fine powders and a carrier gas into a liquid bath[2].

The potential benefits of stirring with CO_2, Ar, or N_2 at 0.1 Nm^3/s into a 100 t heat in an EAF have been estimated by Fruehan[3]. The gas stirring is expected to increase mass transfer by about a factor of 4.

1.1.2 Heat Transfer

The most efficient method of transferring heat to a melt is by producing heat energy within the bath itself rather than by radiation or convection, as is the case in the open-hearth furnace. For arc furnaces, the overwhelming majority of the energy necessary for melting is not produced in the bath itself, but has to be transferred from the arc to the interior of the bath via the slag and the surface of the melt. This leads to temperature gradients and hot and cold spots in the furnace. Injection with an inert carrier gas will cause the bath to be intensely stirred. This will lead to good heat transfer and a homogeneous bath temperature[4].

Riley and Sharma[5] found that gas stirring improved the energy efficiency of the EAF by improving heat transfer. On a relatively small furnace (18 t) using a flowrate of about 0.01 m^3/t, they reported that energy consumption decreased by about 33 kWh/t. In considering the energy consumption, the heat necessary to heat the gas should also be considered. Industrial trials, however, indicate that this is more than compensated for by improved heat transfer, and energy savings of 5 to 10 per cent are observed[5].

1.1.3 High Smelting Rates

The good heat transfer and mass transfer causes the temperature and composition gradients in the bath to be greatly reduced. A near homogeneous melt should be formed, and equilibrium between gas, slag, and metal should be more closely approached. This leads to rapid reactions that make it possible to maintain very high smelting rates. The rate of smelting is ultimately limited by the capacity of the bath to accept unsmelted charge.

1.1.4 Post-combustion

Post-combustion of the CO gas, produced by the reduction reactions, above the molten bath could greatly reduce the electrical energy consumption of the furnace. This will require that the carbonaceous reducing agent is not introduced into the post-combustion region, and that it is effectively utilized below the surface of the molten bath. Submerged injection of the coal may achieve this. Therefore it is necessary to use a submerged top-lance for the injection in case post-combustion is to be implemented at a later stage.

From the above it is clear that the mass transfer and heat transfer in the furnace will be greatly enhanced, and the smelting rates thus increased, by the submerged injection of the reductant with a carrier gas. It was therefore planned to use the solids-injection equipment to investigate the effect of nitrogen stirring, and that of the submerged injection of the reductant into the molten slag bath, on the production of ferrochromium in an open-bath d.c. transferred plasma-arc furnace, using the 200 kVA d.c. facility at Mintek.

2 EQUIPMENT USED

2.1 The Solids-injection System

The solids-injection system was developed for the submerged injection of solids of a size less than 1 mm, at a controlled rate, into a bath of molten material via a submerged top-lance using a gas as the carrier agent. A schematic drawing of the system and a summary of its operating parameters are shown in Figure 1.

2.1.1 The Lance

For the application of injecting coal particles into the slag bath during chromite smelting, it was decided to investigate both an aluminum-diffused steel tube with inside and outside ceramic coating, and a graphite lance with an outer diameter of 50 mm and an inner diameter of 10 mm. The graphite lance consisted of sections of 0.5 m long that were male/female threaded and could thus be screwed together. The inner diameter hole of 10 mm was the smallest that could be drilled through a section of 0.5 m. Graphite has a good resistance to thermal shock, and has high strength at high temperatures, and it was hoped that it would not be consumed quickly in the slag bath because of the reducing conditions in the furnace.

The important parameters in lance design are the length of the lance for given diameter and the material (material in the lance design refers to the surface roughness as characterized by friction factor), upstream stagnation and static pressure, and Mach number and mass flowrate of gas. All these parameters can be determined by conservation equations for the flow of a compressible gas through a lance of constant cross-sectional area. Koria[6,7,8] has done much work on the optimization of gas-injection lance design.

A consumable lance was to be used for the planned testwork, and the rate of consumption had still to be determined. The inner diameter of the lance might also have changed as the particles to be injected passed through it. Furthermore, the furnace size, i.e. distance from the roof to the molten slag bath, determined the minimum lance length. Therefore no effort was made to optimize the lance design, and it was decided that the suitability of the ceramic coated lance and the graphite lance for chromite smelting should rather be determined experimentally during the hot commissioning of the solids injection system.

Angled lances achieve better particle-liquid contact because the particles and gas are largely separated before they leave the lance[9]. Therefore better separation of the injected particles and carrier gas are achieved in the bath, and fewer particles are directly transported by the carrier gas to the off-gas. Thus some inclination of the lance would have been beneficial to

the envisioned testwork. Due to the scale of the testwork, however, the inclination possible was limited by the space in the furnace.

2.1.2 Carrier Gas Velocity Required to Prevent Lance Tip From Clogging

The bubbling-jetting transition of gas jets is an important phenomenon for the submerged gas-injection technique. Liquid penetration into the lance and lance wear are closely related to the bubbling-jetting transition. Liquid penetrates into the lance in the bubbling mode of gas injection, and on solidification will clog it, whereas in the jetting mode no penetration of liquid occurs. Lance wear is also reported to be at a minimum in the jetting mode as compared to its counterpart, the bubbling mode[6].

Many investigators have studied the factors influencing the bubbling-jetting transition by injecting gas through a lance submerged in liquid. According to Mori and co-workers, a sonic velocity at the exit of the lance is essential for the onset of the jetting mode of injection into any liquid[10-12]. McNallen and King support the view that a critical value of the mass flux of gas must be maintained[13]. Farias and Robertson[14] regard the choking of the lance as a necessary condition for the onset of jetting. Sharma[15] has recently investigated the penetration of molten iron into the lance. From the observation of no penetration of melt into the lance, he concluded that neither sonic velocity nor a critical mass flux of gas is a satisfactory criterion for the onset of the jetting mode of injection. A critical value of the modified Froude number had to be reached for the onset of jetting of different gases in molten iron.

Koria[16] has found that the fulfilment of technological requirements (no liquid penetration into the lance and reduced lance tip wear) requires a higher gas-injection rate than that for metallurgical requirements (bath homogenization, and stabilization of mass-transfer-controlled reactions and enhancement of their rates). Any gas-injection rate greater than required to fulfil the metallurgical requirements though, will decrease the tendency of penetration of liquid into the lance, but, at the same time, will increase the intensity of stirring in the bath. In practice, an optimum combination between the required intensity of stirring due to gas injection and the extent of fulfilment of technological requirements must be determined by considering the local plant conditions and constraints.

For the envisioned testwork, where the coal particles were to be injected into a molten bath of slag and metal, the maximum carrier-gas velocity would ultimately be determined by the scale of the testwork. The 200 kVA furnace has an inner diameter of 500 mm, and the slag bath depth would maximally be around 100 mm. High gas flowrates would result in excessive splashing, and it was therefore clear that the bath size would ultimately determine the maximum carrier-gas velocity.

2.2 The 200 kVA d.c. Facility

A description of the facility is given in Appendix A. A schematic drawing of the facility is included as Figure A.1.

3 HOT-COMMISSIONING OF THE INJECTION SYSTEM

The solids-injection system was hot-commissioned at about 1650 °C on chromite smelting using the 200 kVA d.c. transferred plasma-arc facility at Mintek. Both nitrogen stirring of the bath and submerged injection of the reductant into the slag bath was tested.

3.1 Discussion of the Results of the Hot Commissioning

3.1.1 Performance of the Lances Tested

The use of ceramic coated steel tube as lance material proved to be unsuccessful. Due to the high operating temperature the tubing melted away quickly when it was submerged into the slag bath, and was consumed too quickly to make it a viable option for submerged stirring/injection.

Consumption of the graphite lance was much lower than expected. The lance was submerged in the molten slag bath for 50 minutes per heat. During this time it was not necessary to slip the lance further into the melt, since there was only a slight reduction in lance length due to reaction of the graphite lance with the slag. The lance was somewhat eaten away on the sides, however. Total lance consumption was less than 0.2 kg per hour of submerged operation.

The low lance consumption can probably be attributed partly to a thin, protective layer of slag that solidified on the lance. Furthermore, the lance entered the furnace through the roof and, because of space restrictions in the furnace, there was little inclination of the lance. Thus the nitrogen might have formed a protective sheath around the lance as it bubbled from the lance tip to the surface of the molten slag bath, consequently preventing slag/lance contact to some extent. It is also possible that the 'dense' graphite from which the lance was made is relatively inert towards the FeO and Cr_2O_3 in the slag with excess reductant (120 per cent of stoichiometric) in the form of coal or anthracite being present.

3.1.2 Stirring

The nitrogen stirring of the bath proved to be easy to implement. It was found that at a nitrogen flowrate of about 5.7 Nm^3/h (a gas velocity of about 110 m/s at the lance tip),

intensive stirring of the bath was achieved without excessive splashing taking place. At this velocity the lance did not become blocked, even though the velocity was a lot lower than the gas velocities predicted[10-15] to be required to prevent the lance from clogging. At lower flowrates the lance tip tended to become clogged with slag, and thus the flowrate could not be decreased further.

When the slag tapped during stirring was examined, it was noticed that it contained some small dispersed metal droplets. This was due to the agitation of the bath. It was therefore decided to implement a 5-minute settling period at the end of a heat, thus allowing the metal to disengage from the slag before tapping the furnace, for both the stirring and injection conditions.

3.1.3 Injection

It was found that the graphite lance quickly became blocked when coal dust was injected through it. A longitudinal section was cut through the tip of one of the blocked lances (see Figure 2), and it revealed that a graphite-like layer had built up on the inside of the lance. A mineralogical examination of the build-up indicated that it was caused by the ash in the coal melting and then sticking to the inside of the lance.

The injection of pulverized anthracite through the ordinary graphite lance into the molten slag bath proved to be highly successful, with no lance blockages and much more stable operation. The anthracite had only a slightly lower ash content (see Table 1) than the coal dust, and therefore it was felt that the primary reason for the lance not becoming blocked was the fact that the pulverized anthracite was coarser and harder than the coal dust. (The size analyses of the coal dust and the pulverized anthracite are shown in Table 2.) Consequently it had a more abrasive effect in the lance, which prevented it from becoming blocked.

Thus it was found that the physical properties of the material to be injected, i.e. particle size and hardness, were of overriding importance for successful injection.

4 CHROMITE SMELTING CAMPAIGN

After the successful hot-commissioning, it was decided to execute an extended campaign, using anthracite as the reductant, to determine the influence of stirring of the bath and injection of the reductant on chromite smelting. The ferrochromium smelting recipe was determined from published data[17].

4.1 Experimental Programme

Three conditions were to be tested during a continuous campaign on the 200 kVA d.c. facility:

i) Base line: Centre feed of the reductant through the electrode onto the slag bath.

ii) Stirring: Centre feed of the reductant through the electrode, with nitrogen stirring of the bath, using the submerged top-lance of the solids-injection system.

iii) Injection: Injection of the reductant directly into the molten slag bath through the submerged top-lance of the solids-injection system.

The base line was to serve as a basis to compare the influence of stirring and injection. Stirring and injection were to be investigated separately to obtain a better understanding of the rate-controlling mechanism for ferrochromium production.

4.2 Experimental Procedure

It was found that if stirring or injection was implemented right from the start of a heat, it had a detrimental influence on the metallurgical results. This was attributed to the bath being too small at the beginning of a heat to facilitate stirring/injection. The 200 kVA furnace has an inner diameter of 500 mm, and the maximum depth of the slag bath is about 100 mm. Since the bath is drained away to a large extent during tapping, it is clear that little molten material remains in the furnace to stir/inject into at the beginning of a heat. Thus the gas flowrate was probably too high for the bath volume, which would result in molten slag and feed material being blown away from the hot arc-attachment zone below the electrode to the sidewalls, and also in increased material losses of feed to the off-gas, particularly of the relatively light reductant.

It was therefore decided to implement a 'two-stage' operation during the campaign. During the first stage (stage A) all of the chromite and fluxes and about half of the anthracite was fed from the feed hoppers on the mezzanine level through the electrode into the furnace. In this way a relatively large bath of high Cr_2O_3-containing slag (about 20 per cent) was formed. Stage A was the same for all three conditions. During the second stage (stage B) the rest of the anthracite was added to the furnace. For the base line condition this was done by ordinary centre feeding through the electrode. For the stirring condition anthracite was added through the electrode while implementing nitrogen stirring of the bath, and for the injection condition it was injected via the top-lance.

Mass and energy balances were carried out, using the PYROBAL model of the PYROSIM software package[18], to determine the 'theoretical' products and specific energy requirement for the ferrochromium recipe.

The operation of the 200 kVA d.c. facility is controlled by a computer program. The following set-points were entered into the computer program: power, heat losses, specific energy, and feed batch size. The program then automatically balanced the feed rate to the energy input, taking into account downtime, etc.

For the warm-up 60 kg of ferrochromium fines was used as the heel material. The furnace was operated at reduced power levels to heat up the refractories. After about 9 hours, when the heel had become thoroughly molten, heat 1 was started.

As soon as the whole feed batch for a heat had entered the furnace, the power was switched off and the furnace was hydraulically tilted to allow tapping into a refractory-lined ladle. During tapping an optical pyrometer reading of the tapping stream was taken. Spoon samples of the slag and metal were taken from the tapping stream. These samples were then crushed, milled, and analysed.

X-ray fluorescence was used to analyse for the total chromium, iron, calcium, silicon, aluminium, and magnesium content of the slag. The slags were also analysed for metallic chromium and iron to check on the amount of metal entrainment in the slag. This was done by an empirical volumetric procedure with an accuracy of only about 5 to 10 per cent. The carbon and sulphur in the metal were determined by Leco. The phosphorus in the metal was determined by a colorimetric procedure. The chromium, iron, and silicon contents of the metal were determined by ICP-OES (emission spectroscopy with an inductively coupled plasma source).

4.3 Results and Discussion of the Chromite Smelting Campaign

The analyses of the raw materials are found in Table 1, and the average feed and product masses for the three conditions in Table 3. The set-points used for power, voltage, heat losses, and specific energy for the conditions are shown in Table 4. The average operating details for the conditions, i.e. the tap-to-tap time, downtime, energy input, and slag tapping temperature, are also shown in Table 4.

The analyses of the tapped slag for the three conditions are summarized in Table 5. The slag was analysed for both total chromium and iron, as well as metallic chromium and iron (metal entrainment in the slag). The true Cr_2O_3 and FeO content of the slag could therefore be calculated by difference. The average analyses of the ferrochromium alloy produced during the conditions are shown in Table 6.

4.3.1 Influence of Stirring of the Bath and Submerged Reductant Injection on Chromite Smelting

The total Cr_2O_3 content (total chromium content of the slag reported as Cr_2O_3) as well as the true Cr_2O_3 content (chromium actually present in the oxide form in the slag) of the tapped slag were plotted against the heat numbers. Figure 3 shows that stirring of the bath resulted in a clear improvement in the chromite reduction, while injection of the reductant gave much the same level of Cr_2O_3 in the slag as the base line.

During the heats a dip sample was taken of the slag bath at the start of stage B, and thereafter at intervals of approximately 5 minutes until the end of a heat. The dip samples were analysed for both total and metallic chromium content, and thus the decrease in the true Cr_2O_3 content of the slag bath with time could be determined. This data was normalized by dividing the Cr_2O_3 content of the subsequent dip samples by the Cr_2O_3 content of the first dip sample of a heat. An exponential curve was found to fit the data points for each of the three conditions the best. The final result is displayed in Figure 4, which clearly shows that the stirring of the bath resulted in an increase in the rate of Cr_2O_3 reduction. Injection of the reductant gave much the same result as top-feeding of the reductant (base line).

It was felt that the reason for the injection not resulting in an improvement was that the intensity of bath agitation during injection was too high, as far as the metallurgical requirements were concerned, at the minimum gas velocity required to prevent the lance from becoming blocked.

It was found during the hot commissioning that high gas flowrates resulted in excessive splashing, and that the bath size therefore determined the maximum allowable gas velocity. However, at the same time a certain minimum gas velocity of approximately 110 m/s was required to prevent the lance from becoming blocked due to slag penetrating into it.

This velocity appeared to be fine for nitrogen stirring of the bath. However, even though the same nitrogen flowrate was employed for injection, the bath agitation was more violent during injection than during stirring, due to the reductant being introduced below the bath surface in a pulverized form. This resulted in extra gas evolution below the slag surface, and consequently in violent bath agitation. Furthermore, the slag bath was probably too shallow to promote good reductant/carrier gas separation, and thus a significant part of the pulverized reductant was likely to be transported directly with the carrier gas to the off-gas.

5 SUMMARY AND CONCLUSIONS

The graphite lance consumption was much lower than expected (<0.2 kg per hour of submerged operation), and a graphite lance has therefore been proved to be effective in smelting processes. The nitrogen stirring of the bath proved to be easy to implement. A nitrogen velocity of approximately 110 m/s at the lance tip was sufficient to prevent the tip from becoming clogged with slag. The physical properties of the material to be injected, i.e. particle size and hardness, were of overriding importance for successful injection.

Nitrogen stirring of the slag bath increased the kinetics of the chromite smelting. However, injection did not result in an improvement. This was attributed to the bath agitation being too high, as far as the metallurgical requirements were concerned, during injection. This was due to the reductant being introduced below the slag surface in a pulverized form, which resulted in extra gas evolution below the slag surface. Furthermore, the slag bath was probably too shallow to promote good reductant/carrier gas separation and thus a significant part of the pulverized reductant was likely to be transported directly with the carrier gas to the off-gas.

A sufficiently large, and particularly deep, slag bath must be available if stirring and injection are to have a beneficial influence, and the flowrate of the stirring/carrier gas must be balanced to the volume of the bath. Extensive experimental work still needs to be done further to optimize the nitrogen stirring of the molten slag bath, and particularly the submerged injection of the reductant into the slag bath, during chromite smelting in an open-bath d.c. transferred plasma-arc furnace.
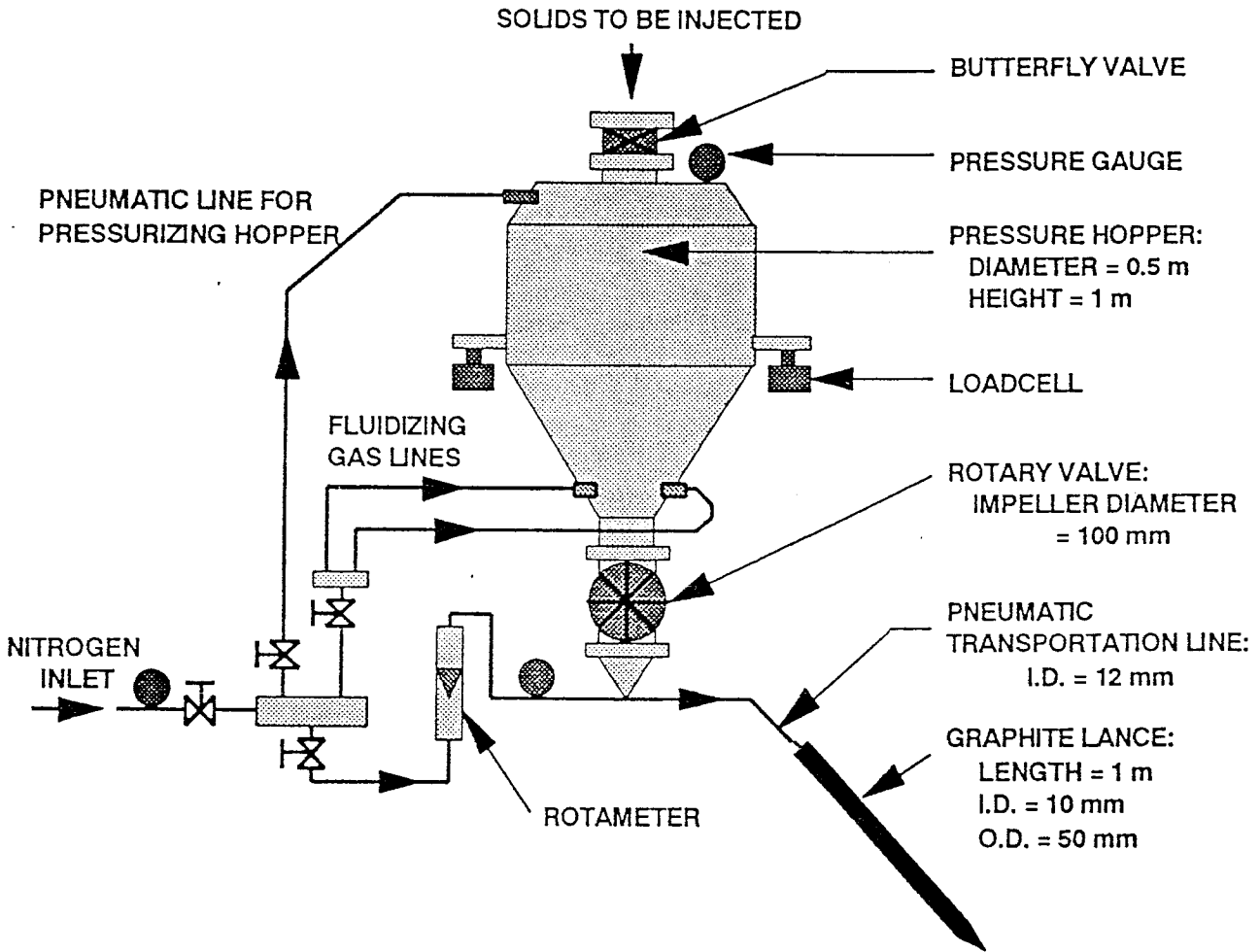
6 ACKNOWLEDGEMENTS

7 REFERENCES

1. FUKAGAWA, S., *et al.* "Smelting reduction mechanism of chromium ore sinter by solid carbon". *Trans. ISIJ*, vol. 27, (1987). pp. 609-617.

2. UPADHYA, K. "An examination of submerged injection processes". *J. Met.*, vol. 35, no. 9, Sept. 1983. pp. 32-36.

3. FRUEHAN, R.J. "Potential benefits of gas stirring in an electric arc furnace". *Iron Steelmak.*, February 1990. pp. 43-50.

4. NORBERG, L.-G. "New vessel for steelmaking by injection". *Metals Austr.*, May 1976. pp. 87-88.

5. RILEY, M.F., and SHARMA, S.K. *I&SM*, June 1987. p. 27.

6. KORIA, S.C. "Modelling of submerged gas injecting lance design parameters". *Steel Res. 60*, 1989, no. 2.

7. KORIA, S.C. "Thermodynamic considerations in designing gas injection lances submerged in melt", *Ironmak. and Steelmak.*, 1989, Vol. 16, No. 1, pp. 21-27.

8. KORIA, S.C. and SINGH, S. "Experimental investigations on the design of gas injecting lances", *ISIJ International, 1989*, Vol. 29, No. 8, pp. 650-657.

9. IRONS, G.A. "Fundamental and practical aspects of lance design for powder injection processes", *4th International Conference on Injection Metallurgy*, Lulea, Sweden, June 11-13, 1986, Proceedings, Part 1, pp. 3 : 11-12.

10. OZAWA, Y., and MORI, K. *Trans. Iron Steel Inst. Jap.*, 1986, no. 26, pp. 291-297.

11. OZAWA, Y., and MORI, K. *Trans. Iron Steel Inst. Jap.*, 1983, no. 23. pp. 764-768.

12. SANO, M., MALINO, H., OZAWA, Y., and MORI, K. *Trans. Iron Steel Inst. Jap.*, 1986, no. 26. pp. 298-304.

13. McNALLEN, M.G., and KING, T.B. *Metall. Trans.*, 1982, no. 13 B. pp. 165-172.

14. FARIAS, L., and ROBERTSON, D.G.C. : in Proc. Conf. "Injection phenomena in extraction and refining", University of Newcastle on Tyne, 1982. *The Metals Society and the Institution of Mining and Metallurgy*, vol. 2. pp. E1-E25.

15. SHARMA, S.K. *Iron Steelmak.*, 1987, no. 14, (3), pp. 73-85.

16. KORIA, S.C. "Consolidation of approaches for bubbling-jetting transition of gas jets in liquid". *Ironmak. and Steelmak.*, 1990, vol. 17, no. 1, pp. 31-37.

17. CURR. T.R. and BARCZA, N.A. The production and treatment of ferrochromium'. Complete patent specification: ZA 827404, Assignees: Council for Mineral Technology and Middelburg Steel and Alloys (Pty) Limited. Lodging date: 11.10.1982.

18. JONES, R.T. Computer simulation of process routes for producing crude stainless steel. M.Sc (Eng.) Dissertation, University of the Witwatersrand, 1989.

FIGURE 1: SCHEMATIC DRAWING AND OPERATING PARAMETERS OF THE SOLIDS INJECTION SYSTEM

SOLIDS TO BE INJECTED

BUTTERFLY VALVE

PRESSURE GAUGE

PNEUMATIC LINE FOR PRESSURIZING HOPPER

PRESSURE HOPPER:
DIAMETER = 0.5 m
HEIGHT = 1 m

FLUIDIZING GAS LINES

LOADCELL

ROTARY VALVE:
IMPELLER DIAMETER = 100 mm

NITROGEN INLET

PNEUMATIC TRANSPORTATION LINE:
I.D. = 12 mm

GRAPHITE LANCE:
LENGTH = 1 m
I.D. = 10 mm
O.D. = 50 mm

ROTAMETER

OPERATING PARAMETERS
NITROGEN LINE PRESSURE AT INLET = 200 kPa
NITROGEN PRESSURE IN PNEUMATIC TRANSPORTATION LINE = 40 kPa
HOPPER PRESSURE = 300 kPa
ROTAMETER: maximum = 28 normal cubic meters/hour
CARRIER GAS FLOWRATE EMPLOYED = 5,7 normal cubic meters/hour
CARRIER GAS VELOCITY EMPLOYED = 110 m/s
ROTARY VALVE: maximum = 50 kg/h of anthracite
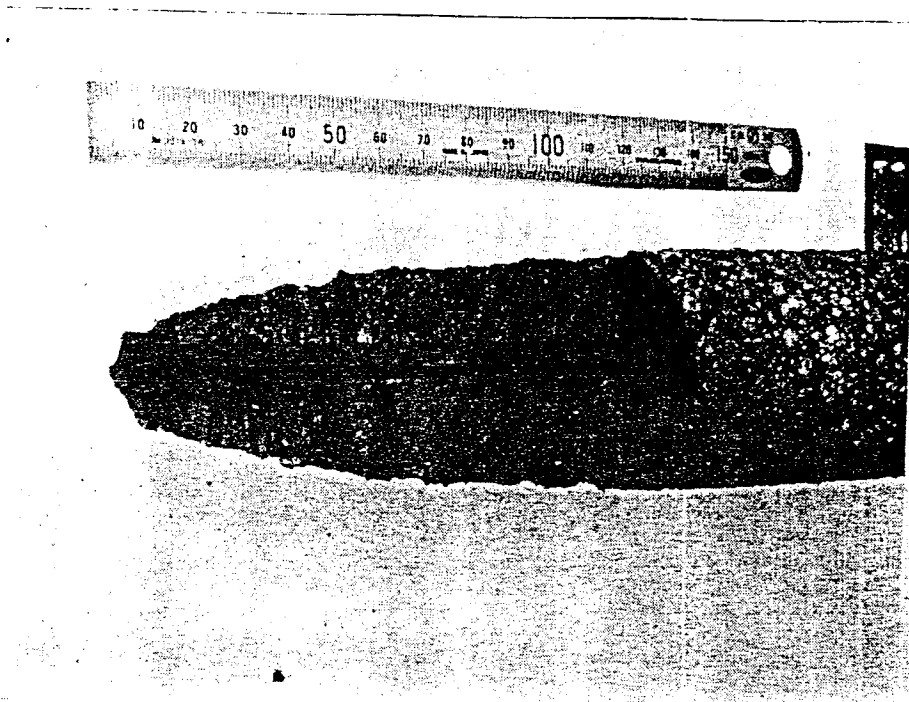
FIGURE 2: SECTION THROUGH THE GRAPHITE TOP-LANCE SHOWING THE
BUILD-UP THAT FORMED WITH INJECTION OF COAL DUST

FIGURE 3: Cr2O3 CONTENT OF TAPPED SLAG
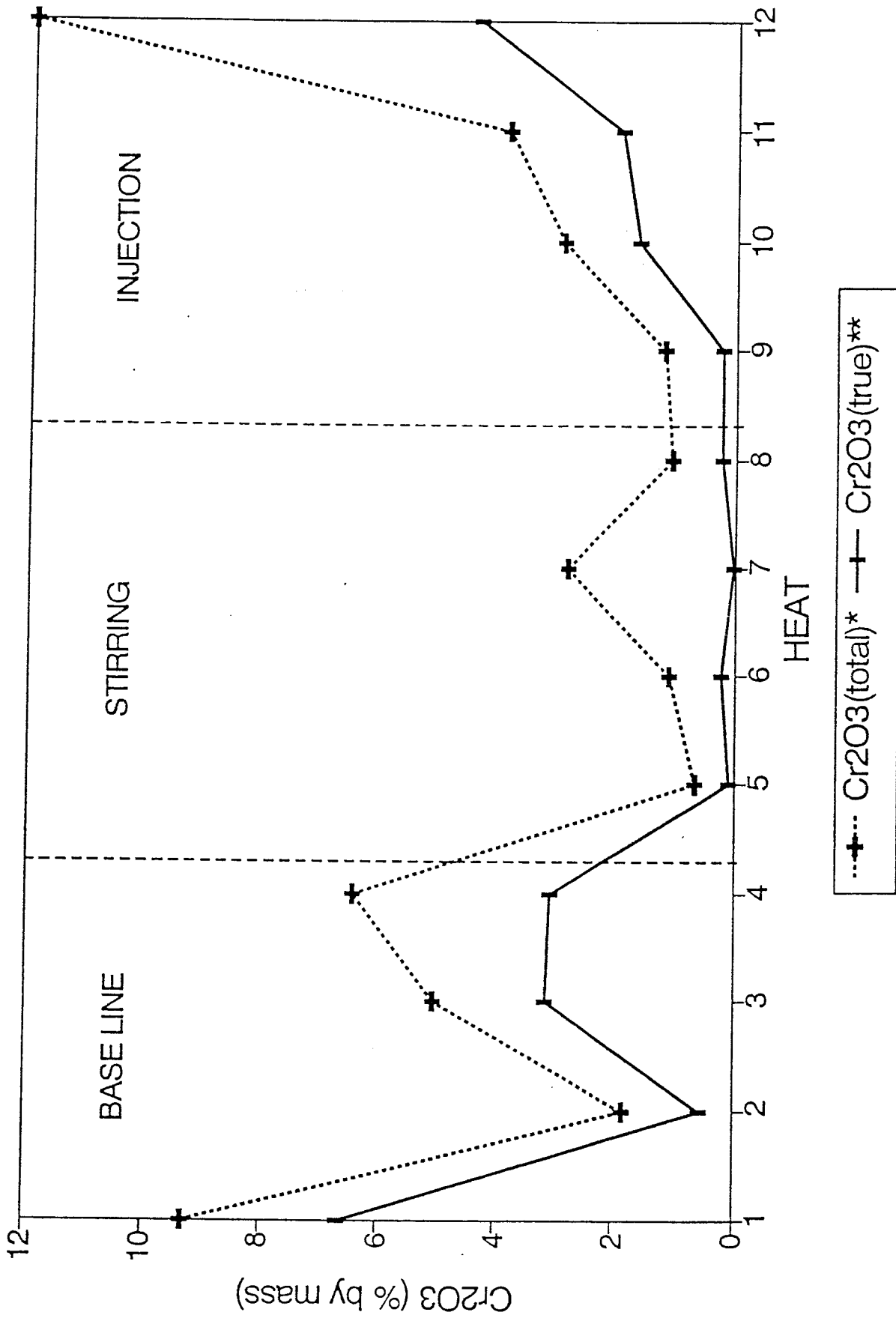
* TOTAL CHROMIUM CONTENT OF SLAG (OXIDES AS WELL AS METAL ENTRAINMENT) REPORTED AS Cr2O3.
** CHROMIUM PRESENT IN SLAG IN OXIDE FORM.

FIGURE 4: DECREASE IN THE SLAG BATH's Cr2O3 CONTENT VERSUS TIME (DIP SAMPLES)

r2-values for fitted curves:
Base Line = 0.95
Stirring = 0.85
Injection = 0.84
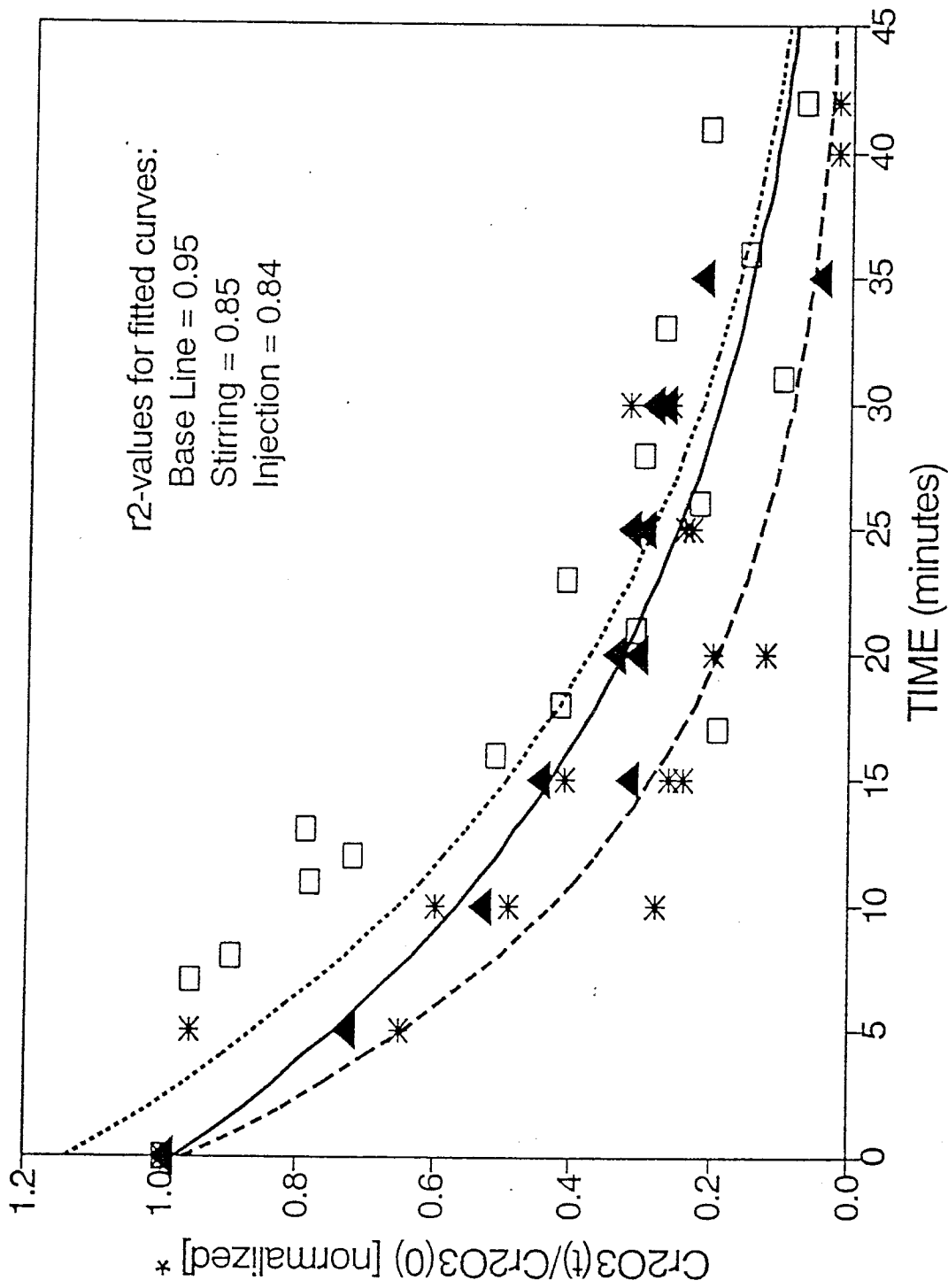
Legend:
- B.L.: FITTED CURVE
- ▲ B.L.: DATA POINTS
- - - - STIR: FITTED CURVE
- ✳ STIR: DATA POINTS
- ········· INJECT: FITTED CURVE
- □ INJECT: DATA POINTS

X-axis: TIME (minutes)

Y-axis: Cr2O3(t)/Cr2O3(0) [normalized] *

* Cr2O3(0): Cr2O3 content of the first dip sample taken of the slag bath at time = 0
  Cr2O3(t): Cr2O3 content of the dip sample taken of the slag bath at time = 't'

TABLE 1

ANALYSES OF RAW MATERIALS

HENRY GOULD CHROMITE COMPOSITION (%)

Cr2O3	Fe2O3	MgO	Al2O3	SiO2	CaO	S	P
43.1	28.2	10.0	14.9	3.09	<0.20	<0.01	<0.01

REDUCTANTS COMPOSITION (%)

	Fixed C	.Ash	Vol.	Analysed on Ash				S	P	Moist.
				SiO2	MgO	Al2O3	CaO			
Coal	54.1	12.6	29.9	51.8	<0.30	34.6	0.89	0.83	0.03	3.4
Anthracite	78.2	11.7	7.4	33.7	1.06	20.2	4.4	1.20	0.01	2.7

FLUX COMPOSITION (%)

	MgO	SiO2	CaO	Fe2O3
Limestone	2.61	2.94	51.9	-
Quartz	-	98.9	-	0.53

TABLE 2

COAL DUST AND PULVERIZED ANTHRACITE PARTICLE SIZE DISTRIBUTION

	Coal Dust		Pulverized Anthracite	
Sieve size micrometer	Mass % Not passing	Mass % Undersize	Mass % Not passing	Mass % Undersize
base	0.5	-	0.3	-
53	2.5	0.5	3.8	0.3
75	10.0	3.0	11.5	4.1
150	20.0	13.0	17.3	15.6
212	39.5	33.0	37.0	32.9
425	24.5	72.5	19.8	69.8
600	3.0	97.0	10.3	89.6
1180	0.0	100.0	0.1	99.9
Total:	100.0	100.0	100.0	100.0

TABLE 3
AVERAGE FEED AND PRODUCT MASSES

Condition	Heat No.	Feed (kg)					Product (kg)		
		HG Chromite	Anthracite	Limestone	Quartz	Batch Total	Metal	Slag	Fume
Warm-Up	0	60 kg Ferrochromium fines					-	-	-
Base Line	1 - 4 Stage A	66.7	10.2	12.2	11.5	100.6			
	Stage B		10.4			10.4	18.0	44.9	3.3
Stirring	5 - 8 Stage A	66.7	10.0	12.1	11.5	100.3			
	Stage B		11.1			11.1	33.1	45.6	3.3
Injection	9 - 12 Stage A	66.0	10.9	12.0	11.4	100.3			-
	Stage B		11.0			11.0	18.8	51.3	5.3

TABLE 4
AVERAGE SET POINTS AND OPERATING DETAILS OF THE CAMPAIGN

Condition	Heat No.	SET POINTS				OPERATING DETAILS			
		Power kW	Voltage V	Heat Losses kW	Specific Energy kWh/kg	Tap-to-Tap Time min	Down Time min	Energy Input kWh	Slag Tap Temperature deg C
Base Line	1 - 4 Stage A	180	120	60	0.87	66	8	154.5	
	Stage B	146	100	60	3.90	40	1	83.0	1643
Stirring	5 - 8 Stage A	180	120	60	0.87	68	14	154.6	
	Stage B	168	100	60	4.90	45	5	96.7	1660
Injection	9 - 12 Stage A	180	120	60	0.87	62	9	149.7	
	Stage B	168	100	60	4.90	43	3	97.0	1671

TABLE 5
AVERAGE PRODUCT SLAG ANALYSES

Condition	Tap No.	Mass kg	Slag Composition (mass %)									
			Cr2O3 (total) *	Cr (metal) **	Cr2O3 (true) ***	FeO (total) *	Fe (metal) **	FeO (true) ***	MgO	CaO	Al2O3	SiO2
Base Line	1 - 4	44.9	5.67	1.6	3.37	2.70	1.6	0.68	18.4	15.0	26.0	34.5
Stirring	5 - 8	45.6	1.42	0.9	0.14	1.04	1.0	0.00	21.7	16.3	26.9	33.5
Injection	9 - 12	51.3	5.09	2.0	2.13	2.80	1.8	0.45	20.7	13.9	26.5	31.6

* Total chromium and iron in the slag reported as Cr2O3 and FeO respectively

** Metallic chromium and iron present in the slag

*** Chromium and iron present as oxides in the slag, obtained by difference from Cr2O3(total) and Cr(metal), and FeO(total) and Fe(metal)

TABLE 6
AVERAGE PRODUCT METAL ANALYSES

Condition	Tap No.	Mass kg	Metal Composition (mass %)						Cr/Fe Ratio
			Cr	Fe	Si	C	S	P	
Base Line	1 - 4	18.0	51.2	36.5	1.60	7.6	0.05	0.006	1.4
Stirring	5 - 8	33.1	52.5	35.4	2.00	8.2	0.03	0.006	1.5
Injection	9 - 12	18.8	51.7	37.0	1.23	7.4	0.06	0.006	1.4

Appendix A

DESCRIPTION OF THE 200 kVA d.c. FACILITY

A schematic drawing of the furnace can be seen in Figure A.1. It shows the water-cooled conical roof with its inclined lance entry and off-gas ports, and with the off-gas ducting in position.

The cathode consists of a hollow graphite electrode to allow centre feeding of the raw materials down the electrode. The anode consists of several steel rods, embedded in the hearth refractory and connected at their lower end to a steel plate which, via radially extending arms, is linked to the furnace shell and further to the anode cable. The furnace shell is lined with a rammable magnesite refractory and the conical roof with an alumina castable.

The feed system is situated on the mezzanine level directly above the furnace, and consists of six feed hoppers. At the bottom of each hopper there is a vibratory feeder. Each hopper with its vibratory feeder is mounted on three load cells. The hoppers feed into two horizontal transfer tubes mounted on vibratory motors with three hoppers per transfer tube. The two transfer tubes feed into a splitter box that is divided into two sections. A flap valve in the splitter box then makes it possible to employ either centre-feeding through the electrode, or side-feeding through a side-feed port in the roof, of the feed materials. During the chromite smelting campaign only centre-feeding of the raw materials was employed.

The fume and dust leave the furnace through the off-gas port. Water-cooled ducting, a 'forced draft' gas cooler, a reverse-pulse bag filter, a fan, and a stack complete the gas-cleaning system. The condensed fume and dust that accumulate in the lower conical section of the bag plant are discharged via a rotary valve into a collecting drum. The off-gas system is designed to ensure complete oxidation of the fumes and gases produced in the furnace. The combustion air is drawn in through the gap between the off-gas port of the furnace and the water-cooled ducting.

FIGURE A.1: SCHEMATIC DRAWING OF THE 200 kVA d.c. FACILITY

FEED HOPPERS

FEED HOPPERS

SPLITTER BOX

TRANSFER TUBE

TRANSFER TUBE

CENTRE FEED TELESCOPE

WATER-COOLED OFF-GAS DUCTING

NITROGEN AND ANTHRACITE PARTICLES FROM SOLIDS INJECTION SYSTEM

STUFFING BOX

OFF-GAS PORT

WATER-COOLED ROOF

ALUMINA CASTABLE

HOLLOW GRAPHITE ELECTRODE
I.D. = 40 mm
O.D. = 70 mm

GRAPHITE TOP-LANCE

FURNACE SHELL
I.D. = 0.5 m
O.D. = 0.8 m

ARC

SLAG

METAL

RAMMABLE MAGNESITE REFRACTORY

ANODE CONNECTION: STEEL RODS EMBEDDED IN HEARTH REFRACTORY

ANODE CABLE